ENERGY YIELD ESTIMATION OF A 75MW PV PLANT IN TAFILALT (MOROCCO). EXAMPLE OF USEFULNESS OF SISIFO TOOL FOR CONTRACTUAL FRAMEWORKS.

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ABSTRACT: This paper describes the technical characteristics and simulates the performance of a 75MW PV plant that is planned by the Moroccan Office National d'Electrecité et de l'Eau potable (ONEE) at Tafilalt, in the South of Morocco. Simulations have been performed using SISIFO, and online and free-software simulator of PV systems.
Keywords: simulation, large grid-connected PV systems.

1 INTRODUCTION

This paper describes the technical characteristics and the simulation results for a 75MW PV plant, which is planned by the ONEE in Tafilalt, in the South of Morocco. This study has been performed using a simulation tool, called SISIFO [1], which has been developed by IES-UPM under the European project PVCROPS [2][3].

The PV plant is composed of $250W_p$ mono-crystalline silicon modules mounted on either static structures or one horizontal-axis trackers, which remains to be decided. The plant is divided into 50 individual grid-connected systems, each one composed of two PV arrays of $750kW_p$ (3000 modules) that inject energy to a medium voltage power station composed of two 800kW inverters and one 1.6MW LV/MV transformer.

The following sections provide an overview of the simulation assumptions and modelling, and describe the information and input parameters that have been used in the simulation.

2 SIMULATION OF THE TAFILALT PV PLANT

This section describes the input parameters that have been used in the simulation, which are explained in the same order that appear in the web interface [1], in order to serve as a guide of how to perform a full simulation exercise.

2.1 Location

Tafilalt PV plant is located 8 km southward of Zagora city, in the region called Souss-Massa-Drâa. The geographic coordinates of the PV plant are:

- Latitude: 30.27°N
- Longitude: -5.83°E
- Elevation: 783 m

2.2 Meteorological input data

Meteorological data, which has been provided by the ONEE, consist of 365 values of daily global horizontal irradiation, and minimum and maximum ambient temperatures.

For simulation purposes, the monthly means of the daily series have been calculated, which are displayed in Table 1. The additional Linke turbidity data has been obtained from the PVGIS database [4]. The corresponding yearly global horizontal irradiation of the location is 2185.6 kWh/m^2.

Table 1: Monthly mean values of the horizontal daily irradiation (*Gdm0*), minimum (T_{mm}) and maximum (T_{Mm}) ambient temperatures, and Linke turbidity (T_{LK}), used in the simulations.

	Gdm0 *Wh/m²*	T_{mm} °C	T_{Mm} °C	T_{LK}
January	3947	4.6	20.8	3.3
February	5089	6.6	23.4	4.3
March	6181	10.4	26.3	3.6
April	7363	15.0	32.7	4.5
May	7308	21.0	36.6	4.5
June	8102	23.8	39.3	5.4
July	7525	27.2	43.6	6.0
August	7234	26.1	41.8	6.1
September	5708	20.5	34.5	5.8
October	5314	17.6	34.5	5.0
November	4402	9.8	25.6	4.7
December	3647	4.8	19.0	4.1

It is assumed that the cooling effect of the wind on the PV generators is equivalent to consider that the difference between module and ambient temperature is equal to the incident irradiance multiplied by the factor 25.9 °C/(kW/m^2).

2.3 PV modules

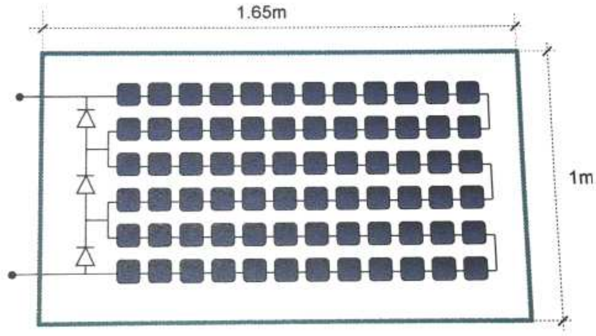
The technology of the PV modules is mono-crystalline silicon. The manufacturer only provides the nominal power under Standard Test Conditions (STC), $250W_p$, so the simulation has been performed with the power model called "Only temperature effects" because there is no data of module efficiency to take into account losses at low irradiances. Despite its simplicity, this model explains up to 98% of the observed variability [5].

The model requires two values from the manufacturer datasheet: the coefficient of variation of power with temperature, γ, and the nominal operation cell temperature, NOCT, which is used to calculate the cell temperature from the ambient one. Table 2 displays these characteristics:

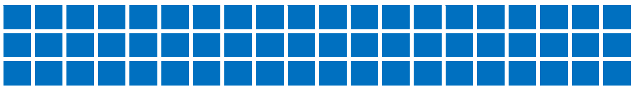
Table 2: Model parameters used in the simulations.

PV technology	γ (%·°C^{-1})	NOCT (°C)
Si-c	0.3	43

Each module has three bypass diodes, whose electrical layout and dimensions are displayed in Figure 1a.



(a)



(b)

Figure 1: (a) Electrical layout of the PV module (landscape orientation). The group of cells protected by the bypass diodes is 1 in the horizontal dimension and 3 in the vertical dimension. (b) Each structure supports 3x20 modules in landscape orientation.

2.4 PV generator

The PV generator is constituted by 100 PV arrays. Each PV array is composed of 3000 modules of 250W$_p$, which gives a nominal power of 750kW$_p$ per array. It remains to be decided installing the PV modules either on static structures or on one horizontal-axis trackers. Hence, both options have been simulated and compared. In both cases each supporting structure has 3 vertical x 20 horizontal PV modules in landscape orientation (see Figure 1b). The number of blocks (groups of cells protected by bypass diodes) is 9 in the vertical dimension and 20 in the horizontal dimension.

Two PV arrays, each one with 750kW$_p$, inject energy to a medium voltage power station, which is composed of two 800kW inverters and one 1.6MW LV/MV transformer whose nominal output voltage is 30kV. Table 3 summarizes the characteristics of the PV generator and Table 4 the loss scenario, which lumps together the following possible loss factors:

- Underrated PV modules.
- Initial light induced degradation.
- Electrical characteristics mismatching.
- Orientation temperature mismatching.
- DC wiring of the PV generator.
- Imperfect maximum power point tracking (MPPT) of the PV generator.
- Lower than anticipated DC/AC and LV/MV conversion efficiencies.

Table 3: Electrical parameters of the PV generators

Parameter	Value
System nominal power	75,000kW$_p$
Nominal PV power per inverter	750kW$_p$
Nominal PV power per transformer	1,500kW$_p$
Real Power – Nominal Power ratio	0.95
Bypass diodes – horizontal (NBGH)	20
Bypass diodes – vertical (NBGV)	9

Table 4: Loss scenario

Loss Factors	Value (%)
Underrated PV modules	1
Initial light degradation	0.5
Mismatching	1
Imperfect MPPT	1
DC wiring	0.5
DC/AC and LV/MV conversion efficiencies	1

Next sections define the geometrical parameters used in the simulation for the static and the sun-tracking structures. The GCR is assumed to be the same for static and tracking structures, which is not usually the case.

2.4.1 Static structure

The parameters of the selected static structure are displayed in Table 5.

Table 5: Parameters of the ground PV generator.

Parameters	Value
Roof inclination (β_R)	0
Roof orientation	0
Generator inclination (β_G)	29^o
Generator orientation	0
Separation among structures N-S (L_{NS})	2
PV generator width (A_{EO})	11
Deviation of back structure (D_{EO})	0

The North-South separation between structures has been selected as a compromise between the reduction of shading losses and the increasing of the ground area.

2.4.2 One-axis North-South horizontal solar tracker

The parameters of the selected one axis horizontal tracker are displayed in Table 6. The East-West separation between structures has been selected as a compromise between the increasing of electricity production and the increasing of the ground area.

The PV plant produces more than 14% of electricity in comparison with the static structure (see section 3).

Table 6: Parameters of the one-axis horizontal tracker.

Parameters	Value
Separation between trackers in E-W direction (LEO)	2
Maximum rotation angle (θ_{MAX})	60^o
Axis orientation	0
Axis inclination (β_{AXIS})	0
Separation between trackers Rows in N-S direction (L_{NS})	1
Module inclination (β_G)	0
Backtracking option – horizontal	Yes

The backtracking option selected means that the tracker rotates with respect to the horizontal axis to avoid shading.

2.5 Balance-of-system components (BOS)

Two PV arrays are connected to a low voltage/medium voltage (LV/MV) power station that is constituted by two inverters and one LV/MV power transformer, whose characteristics are described in Table 7.

Table 7: BOS parameters.

Parameters	Value
Inverter	
Nominal Power	800kW
Maximum Power	898kW
Power efficiency curve	Introduce inverter curve
$\eta_{P=100\%}$	98.1%
$\eta_{P=50\%}$	98.4%
$\eta_{P=10\%}$	97.8%
Transformer	
Nominal Power	1,600kW
Iron Losses	1,7kW
Copper Losses	14kW
Wiring	
DC Losses	0.5%
AC/LV Losses	0.5%

Inverters have a nominal power of 800kW with a maximum of 898kW. The power efficiency curve of the inverter has been indicated using the three efficiencies provided by the manufacturer at 10%, 50% and 100% of the nominal power.

The transformer has a nominal AC output voltage of 30kV and a nominal power of 1600kW. Iron and copper losses are obtained from the manufacturer datasheets.

It is assumed that the aggregated non-ideal energy losses, which are due to DC and internal wiring, to the differences between the real and the nominal characteristics of the main components (PV modules, inverters and transformers) and to the auxiliary services, stand up to 5%. Moreover, wiring losses at STC power stand at 1% (0.5% DC and 0.5% LV).

2.6 Simulation options

The first two options, "PV application" and "Analysis Type", are predefined in this version of SISIFO to, respectively, grid-connected PV systems and yearly analysis. The option "Optimum slope" that maximize the caption of energy of the static structure in the plane of array has not been selected because this parameter has been optimized using the simulations.

The impact of soiling has been considered in 2%, although it may be an optimistic estimation taking into account that the PV plant will be installed in a desert region.

The selected options are the recommended values in SISIFO, are displayed in Table 8.

Table 8: Selected advanced options for the simulation.

Option	Selected value
Spectral Response	No
Diffuse radiation modeling	Hay
Shading model	Martinez
Minimum irradiance	0 W/m^2
Ground reflectance	0.2
Daily diffuse correlation	Erbs
Uncertainties	
Global horizontal yearly irradiation	5%
Yearly inter-variability of the global horizontal irrad.	1%
Long-term variability of the solar resource	0%
Transposition models and operating cell temp.	2%
Power response of PV generators and inverters	2%
Initial PV power	2%
Long-term PV power degradation (Ageing)	0.3%

3 SIMULATION RESULTS

3.1 Yearly energetic balances

Table 9 summarizes the yearly energetic balances that describe the operation of the Tafilalt PV plant for both the static ground-mounted and tracking structures.

Table 9: Yearly energetic balances for the ground-mounted static and horizontal tracking structures. Data marked in bold-italic belong to the horizontal tracking structure

Solar radiation balance				
$G_a(0)$ *kWh/m^2*	$G_a(I)$ *kWh/m^2*	$G_{efa}(I)$ *kWh/m^2*	$G_{efsaypa}(I)$ *kWh/m^2*	$G_{efsaypcycea}(I)$ *kWh/m^2*
2186	2442	2312	2302	2302
2186	***2753***	***2639***	***2639***	***2639***

Energy balance				
E_{DC}/P_{NG} *kWh/kW*	$E_{AC},LV/P_{NG}$ *kWh/kW*	$E_{AC},MV/P_{NG}$ *kWh/kW*	*P75* *kWh/kW*	*P90* *kWh/kW*
2041	2001	1981	1887	1802
2327	***2283***	***2260***	***2153***	***2056***

The nomenclature of the parameters is described in section ANNEX (Nomenclature).

On the other hand, it is a general rule in the photovoltaic field to describe the energy chain of a photovoltaic system by means of the following parameters (see Table 10):

Capture losses $L_C = 1 - \left(E_{DC}/\left(P_{NG} \cdot G_a(I)\right)\right)$

System losses $L_S = 1 - E_{AC}, HV/E_{DC}$

Specific productivity $Y_F = E_{AC}, HV/P_{NG}$

Performance Ratio $PR = Y_F/[G_a(I)/G^*]$

Table 10: Results of the performance parameters.

Performance parameters			
L_C *%*	L_S *%*	Y_F *(MV)* *kWh/kW*	*PR* *%*
16.4	2.4	1981	81.1
15.5	***2.4***	***2260***	***82.1***

4 CONCLUSIONS

The simulation of a 75MW PV power plant planned by ONEE and located in Tafilalt (Morocco) has been carried out using SISIFO, a free-software web application for the simulation of PV systems, in order to illustrate the capabilities of this tool.

Simulations have been performed for two types of PV generators, static and one-axis horizontal solar trackers, whose selection remains to be decided in the project.

For the static structure, the predicted yearly energy production of the plant is *148575 MWh*, which is equivalent to a Final Energy Yield Y_F *= 1981 kWh/kW* and Performance Ratio *PR = 0.811*.

For the horizontal one-axis tracker, the predicted yearly energy production of the plant is *169500 MWh*, which is equivalent to a Final Energy Yield Y_F *= 2260 kWh/kW* and Performance Ratio *PR = 0.821*.

ACKNOWLEDGEMENT

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ANNEX: NOMENCLATURE

Parameter	Description
$G_a(0)$	Global horizontal irradiation
$G_a(I)$	Global incident irradiation on the PV array
$G_{efa}(I)$	Global effective incident irradiation on the PV array
$G_{efsaypa}(I)$	Global effective incident irradiation on the PV array, taking shade into account
$G_{efsaypcea}(I)$	Global effective incident irradiation on the PV array, taking shade and spectral correction into account
E_{DC}/P_{NG}	DC energy production divided by the PV power nameplate
$E_{AC},LV/P_{NG}$	AC energy production at the inverter output divided by the PV power nameplate
$\mathrm{E_{AC},MV/P_{NG}}$	AC energy production at the LV/MV transformer output divided by the PV power nameplate
P75	AC energy production at the LV/MV transformer output divided by the PV power nameplate that is exceeded 50% of time
P90	AC energy production at the LV/MV transformer output divided by the PV power nameplate that is exceeded 90% of time

Energy Yield Estimation of a 75 MW PV plant in Tafilalt (Morocco). Example of usefulness of SISIFO tool for contractual frameworks

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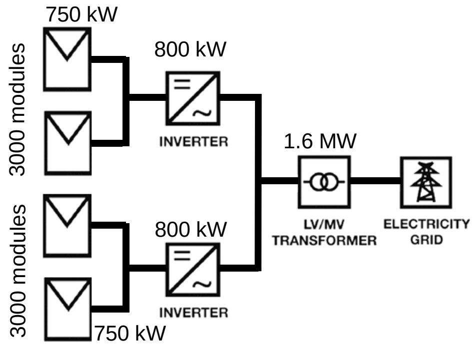
1. INTRODUCTION

- The information related to the constitution of the power station has been provided by the ONEE. Other information has been provided by IES-UPM.
- Simulation developed by IES-UPM using SISIFO.
- 50 individual grid-connected systems.
- 250 W_p monocrystalline silicon module.
- Static or one horizontal-axis tracker (remains to be decided).



2. SIMULATION

LOCATION	
Latitude	30.27ºN
Longitude	-5.83ºE
Altitude	783 m

PV MODULES (Si-c)	
P*	250W_p
γ	0.3 %·ºC^{-1}
NOCT	43ºC

STRUCTURES	
Inclination	29º
Max. Rotate angle (tracker)	60º
Backtracking (tracker)	Yes

INVERTER	
Nominal Power	800kW
Maximum Power	898kW
$\eta_{P=100\%}$	98.1%
$\eta_{P=50\%}$	98.4%
$\eta_{P=10\%}$	97.8%

TRANSFORMER	
Nominal Power	1,600kW
Iron Losses	1.7kW
Copper Losses	14kW

LOSSES	
Soiling	2%
Wiring – DC	0.5%
Wiring – AC	0.5%

OPTIONS	
Spectral response	No
Diffuse radiation modeling	Hay
Shading model	Martínez
Minimum irradiance	0 W/m^2
Ground reflectance	0.2
Daily diffuse correlation	Erbs

UNCERTAINTIES	
Global horizontal yearly irradiation	5%
Yearly intervariability of the global horizontal irradiation	1%
Long-term variability of the solar resource	0%
Transposition models and operating cell temperature	2%
Power response of PV generators and inverters	2%
Initial PV power	2%
Long-term PV power degradation (Ageing)	0.3%

3. RESULTS

- These results rely on the asumptions:
  - The GCR is assumed to be the same for static and tracking structures, which is not usually the case.
  - Aggregated non-ideal energy losses stand up to 5%. Moreover, wiring losses stand at 1%.
  - Soiling losses at normal incidence are 2%.

Ground-static STRUCTURE	
Production (MWh)	148575
Final Energy Yield (kWh/kW)	1981
PR	0.811

One horizontal-axis TRACKER	
Production (MWh)	169500
Final Energy Yield (kWh/kW)	2260
PR	0.821

SISIFO
www.sisifo.info